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Effects Of Position, Orientation, And Infiltrating Material On Three Dimensional Printing Models

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EFFECTS OF POSITION, ORIENTATION, AND INFILTRATING MATERIAL ON
THREE DIMENSIONAL PRINTING MODELS

by

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B.S. Florida State University, 2002

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Mechanical, Materials, and Aerospace Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
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2007

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ABSTRACT

This research defined and evaluated mechanical properties of prototypes created using a plaster based three-dimensional printing (3DP) system commercialized by Z Corporation. 3DP is one of the fastest growing forms of rapid prototyping. Till date, there is little or no information available on material properties of infiltrants used in 3DP. This research work evaluated and documented some of the useful information for 3DP users by determining the effect of build position, build orientation and infiltration materials on the strength of prototypes.

The study was performed in three different phases to limit the processing variables and to arrive at definite conclusions on relationship between materials properties and process variables. All specimens were built on the Z Corporation Spectrum Z510. In *Phase 1*, effects of build location on specimen strength was studied. *Phase 2* evaluated the influence of build orientation on specimen strength. System Three Clear Coat epoxy was used during both *Phase 1 and 2* for infiltration. The same infiltrant was in both of these phases to limit variables. Using results of *Phase 1 & 2*, the effects of infiltrant material on tensile strength of prototypes was calculated in *Phase 3*. Seven different infiltrating materials were tested during *Phase 3*. These materials included 2 cyanoacrylates and 5 epoxies. The tensile strength, flexural strength, and density and porosity of the specimens were determined and correlated. In each phase six specimens were built for each test performed. Two consistent methods of infiltration were utilized to infiltrate cyanoacrylates and epoxies into the as-processed specimens.

It was found that the orientation of the specimen has more of an impact on strength than position within the build platform. The layering build process of rapid prototyping creates a variance in strength depending on the build orientation. Specimens infiltrated with epoxy achieved much higher strength than the specimens infiltrated with cyanoacrylate. Cyanoacrylates may be a good choice in making color concept models; however they are not good candidate materials where strength requirement is important. The epoxies with lower viscosities demonstrated higher part strength among the materials tested.

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LIST OF ACRONYMS

3DP	Three Dimensional printing
CA	Cyanoacrylate
DDM	Direct Digital Manufacturing
FDM	Fuse Deposition Modeling
MJM	Multi-Jet Modeling
RP	Rapid Prototyping
RT	Rapid Tooling
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	Stereolithography file
UV	Ultra Violet

CHAPTER ONE: INTRODUCTION

1.1 Motivation

The Rapid Prototyping (RP) industry has become a fast growing and ever changing family of technologies. Rapid prototyping (also known as layered manufacturing or additive fabrication) consists of several different types of technologies such as stereolithography [1], selective laser sintering [1, 2], fused deposition modeling [3-5], three-dimensional printing (3DP) [6] and several others [1, 7]. These technologies are used to create physical prototypes, models, tooling components, and other physical parts from CAD data. Rapid Prototyping was first introduced in 1987 in the form of stereolithography it used a laser to cure UV sensitive material layer by layer. The RP technologies are being used in all different types of design and manufacturing organizations. In recent years, the industry has experienced a large push towards office friendly 3D printers, which are low cost office friendly RP machines. However, there is still a need for information on printing techniques, materials used, build orientation, infiltration agents, and material strengths for 3DP [8]

Z Corporation (ZCorp) introduced its first 3DP, the “Z402” in 1996 [9]. The first 3DP used a starch or plaster based powder material with a water-based binder [9]. The prototypes produced with this process displayed low strength and were used for concept models. Towards the end of 2000, ZCorp introduced the first commercial color RP system “Z402C” [10]. Following, the Spectrum Z510 was introduced in 2005. It can print in full 3D color and is mostly being used in non-functional prototyping such as

architectural, medical and consumer product models. The Z Printers excel in the industry as a low-cost fast-prototyping machine. Z Corporation has increased the total number of machine sales from 461 in 2004 to 687 in 2005 [9]. This increment in total number of users has increased the need for new infiltrants and mechanical strength data for infiltrated parts. Little, if any information is published or available on mechanical behavior of prototypes built with the Z Corporation 3DP process.

The objective of this project is to identify and compare several different infiltrating materials, and also to determine the effects of build position and build orientation on part strength. The strength of parts can vary greatly based on the infiltrants used in the post processing stage. It is believed that infiltrating materials determine the majority of strength of rapid prototypes built with the Z Corporation's "3DP". Knowing the mechanical behavior of several different infiltrants will allow the operator to use the technology more efficient building for creating functional prototypes. By determining the strength of the parts with different infiltrants, it provides the possibility of new applications both in rapid tooling and part production. Rapid tooling is using the process of using rapid prototyping technologies to produce tooling and tooling inserts directly on the RP machine [11]. Almost any material with a relatively low viscosity that will harden can be used as an infiltrant, such as wax, urethanes, epoxies, cyanoacrylates, etc. High-temperature epoxies can be used in several applications such as molds, fixtures and other rapid tooling applications. Prototypes infiltrated with a high-temperature epoxy can be used as molds and other rapid tooling. The information from this research will provide the proper infiltration material selection for the application.

1.2 Research Objectives

The objective of this research project is to identify strength of infiltrated prototypes built with the Z Corporation Spectrum Z 510. The specific objectives are:

Specific Aim 1: To study the effect of build position and orientation on tensile properties of epoxy infiltrated prototypes created in 3DP Z Corporation RP machine.

Specific Aim 2: To determine the effects of infiltration material on tensile properties of prototypes created in 3DP Z Corporation Z510 RP machine.

Specific Aim 3: To determine the effects of infiltration material on flexural strength of prototypes created in 3DP Z Corporation RP machine.

Specific Aim 4: To compare and correlate tensile strength of prototypes with their porosity and how are they affected by 3DP processing variables.

1.3 Research Plan

This research was designed to classify infiltrating materials for the Z Corporation Spectrum Z510. The ideal build location and orientation of prototypes built with the Spectrum Z510 was determined. Testing of epoxy infiltrated parts built in six different build zones was performed to determine the strength variance between zones. Then samples were built in nine different orientations and infiltrated with epoxy and tensile

testing was performed. The build location and orientation strengths were determined and used to select the location and orientation for testing seven different infiltrants. The flexural and tensile strength of prototypes infiltrated with the seven materials was determined. The density and porosity of infiltrated prototypes was determined and correlated with the tensile strength of the prototypes. This information is used to classify the infiltrating materials used.

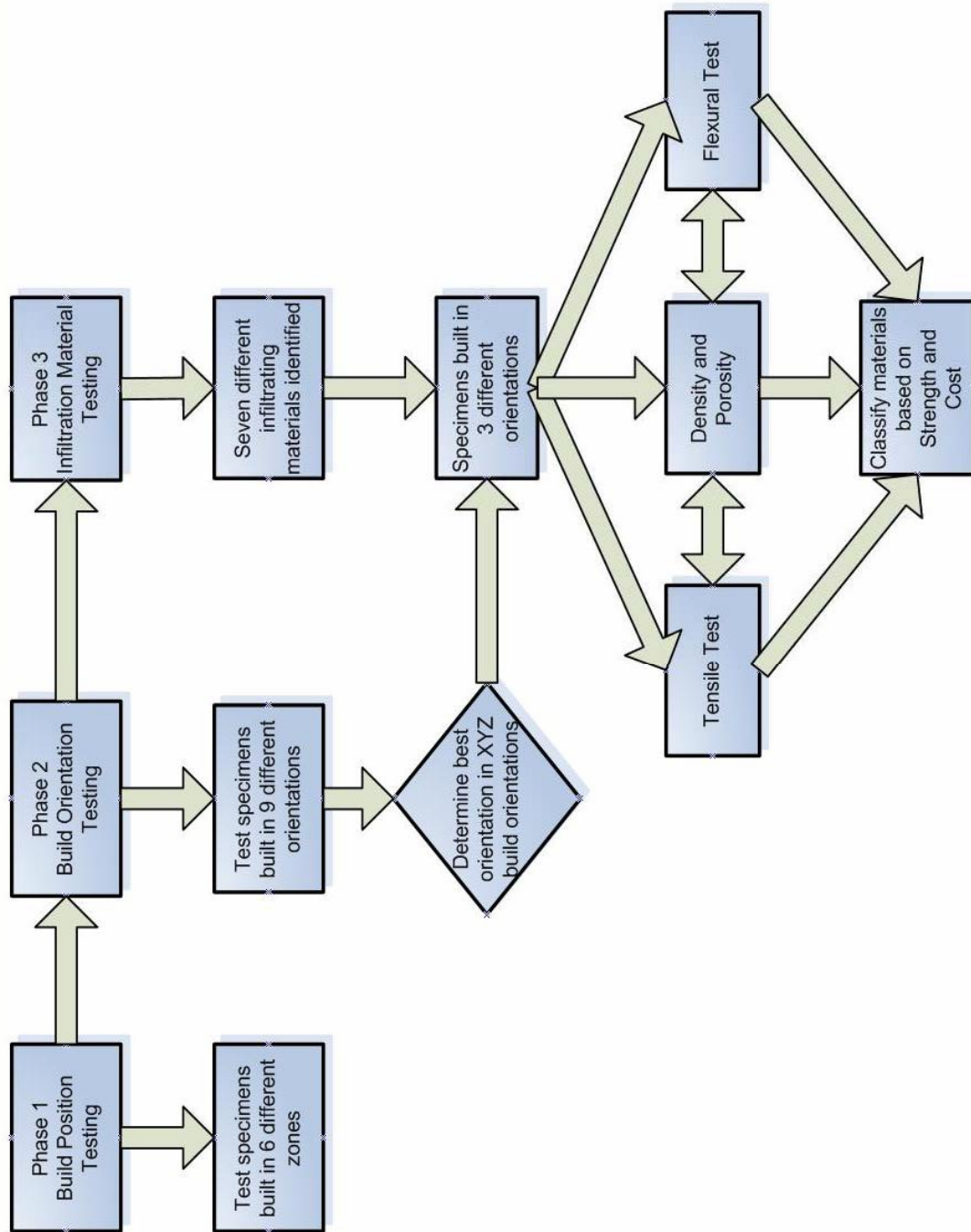


Figure 1: Research Plan

CHAPTER TWO: LITERATURE REVIEW

2.1 Rapid Prototyping Systems and Industry Use

Rapid prototyping, also known as layer manufacturing, consists of several different technologies. RP machines vary in size and building method and build materials but they all build in a layering method. The main classes of RP machines are: Stereolithography (SLA), Selective Laser Sintering (SLS), Multi-Jet Modeling (MJM) and Three Dimensional Printing (3DP).

SLA is the oldest RP technology and one of the most widely used. The SLA process consists of a vat of liquid resin and a laser to solidify the resin layer by layer. Several manufactures produce SLA machines with varying build envelopes and layer thicknesses. The standard layer thickness for an SLA machine is 0.05 mm for a standard resolution machine. A benefit of SLA is the variety of materials that can be selected for use. Materials vary from ABS like to ceramic filled resins to produce high strength and temperature resistance. SLA machines use a support structure that has to be removed after the part is complete.

The SLS process use a laser to sinter a powder material spread onto the build platform. SLS uses a similar method to that of the Z Corporation 3DP with a feed platform and a build platform. A powder material is spread from a feed platform to the build platform where the cross section is sintered by a laser. The standard layer thickness for the SLS process is 0.1mm. The SLS process has a variety of materials available from plastics, nylons, flexible materials and metals.

Multi-Jet Modeling is a newer technology that uses a UV light to cure a UV curable resin that is deposited layer by layer. The resin is deposited by a print head assembly in the correct cross section and then cured by the passing UV lamp. The material is cured up to three layers deep helping to eliminate the weakness between layers of RP parts. The layer thickness of MJM machines depends on the manufacture; it can range from 0.0150 – 0.0254 mm. The MJM machine uses a self contained material cartridge instead of the vat of resin like SLA. For this reason it is seen as a more office friendly machine. In the industry, 3DPs are considered to be office friendly and entry level systems.

2.2 Three Dimensional Printing in Industry

The term 3DP has grown to consist of several technologies including: Stratasys' Dimension FDM, 3D System's Invision and Thermojet MJM, Objet Polyjet, SolidScape MJM, and the Z Corporation 3DP. The lower cost office friendly machines are becoming grouped as 3DP.

Based on conducted surveys, Terry Wohlers of Wohlers Associates stated that functional models will account for the majority of prototypes produced by the rapid prototyping industry [9]. While there has been research conducted on the accuracy of the 3D printers, little to no public work has been performed for the strength and mechanical properties of models. For prototypes to be successfully used as functional models, more research will be required in this area.

Z Corporation introduced its first 3DP the Z402 in 1996. The first 3DP used a starch or plaster based powder material with a water-based binder [9]. The Spectrum Z510 was introduced in 2005. It can print in full 3D color and is mostly being used in non-functional prototyping such as architectural, medical and consumer product models. The Z Printers excel as low cost fast prototyping machines.

2.3 Z Corporation Three Dimensional Printer Operation

The Spectrum 510 is a powder-based 3DP system that uses print heads to jet a binder onto the bed of powder. The build area of the printer consists of two platforms, a feed platform and a build platform, as well as a printing assembly (Figure 2).

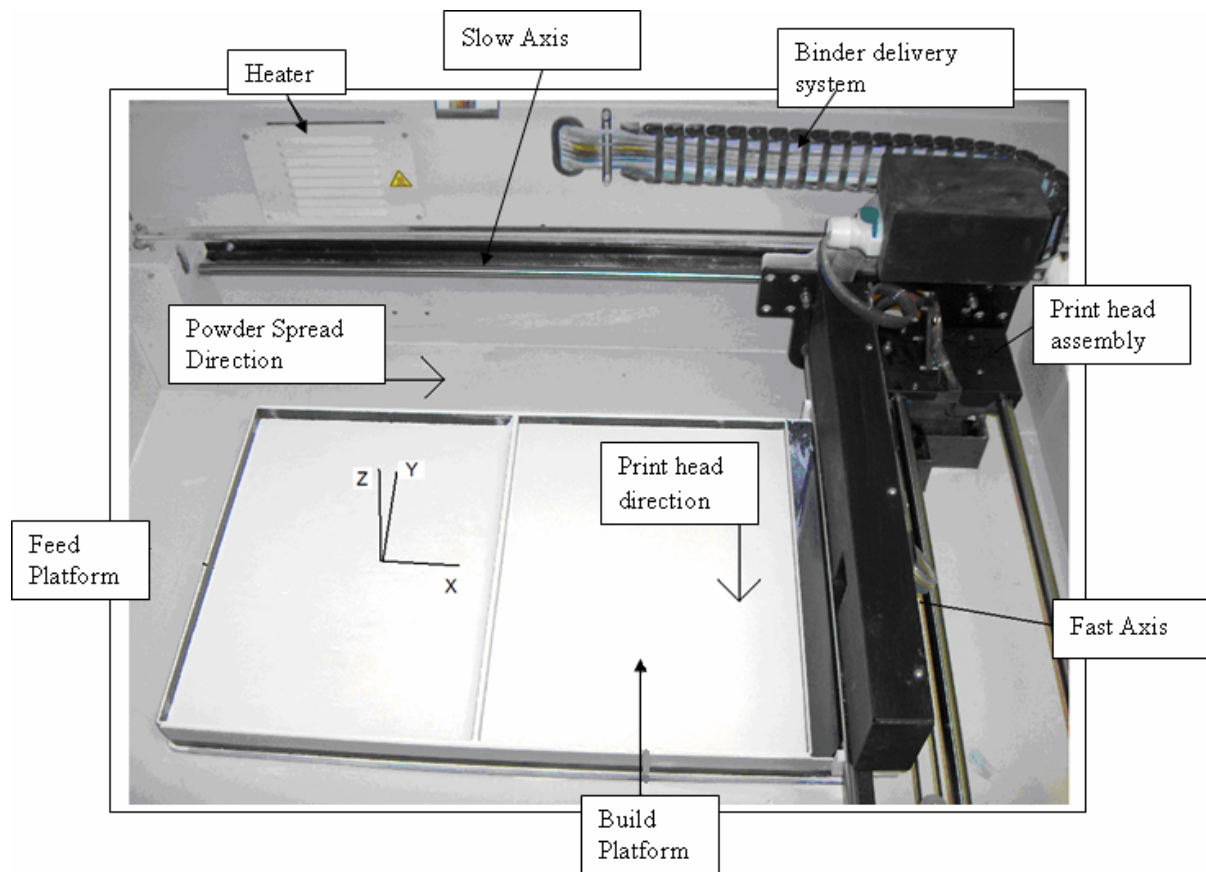


Figure 2: The build area of the Spectrum Z510 and schematic of the Z Corporation 3D printer.

The preprocessing software will slice the 3D part into 2D slices and send the slices to the printer. The print head assembly will move from right to left depositing binder for each 2D slice of the part. The print head travels from back to front depositing binder, this is also known as the fast axis. Once the layer is completed the build platform (Z-axis) lowers a layer and the feed platform rises to spread powder to the build side. A roller spreads the powder from the feed side to the build (left to right) for

each layer of the part. The layer thickness can be adjusted from 0.089-0.102 mm. The build envelope for the Spectrum Z510 is 254 mm x 355.6 mm x 203.2 mm. The entire process is repeated until the part is complete.

The print head assembly uses four standard Hewlett Packard # 11 ink jet print heads to deposit a liquid adhesive binder (one for each color; clear, magenta, cyan, and yellow) onto the bed of powder layer by layer (Figure 1). The print heads are installed into the print head carriage and the black ink is purged out. Once this is complete the print heads are aligned to ensure the proper building. The print heads have a build life of approximately 1100mL of binder deposited [12, 13]. The print quality will decrease as the print head approaches this limit and the part quality will be affected.

The Z Corporation 3DP does not use support structure because the unbound powder acts as support structure. Upon completion of the build, the part is encased in loose powder that is then brushed away to remove the part. The part is currently in the green state and is relatively delicate, therefore it needs to be infiltrated with a material to increase the strength. Parts directly removed from the machine can contain moisture, which will inhibit the infiltration process and possibly decrease strength. To ensure all of the moisture is removed from the parts they are baked in a convection oven. The parts, specifically the binder, will start to break down if baked at too high of a temperature. Due to its flexibility and dimensional accuracy, 3DP systems can be used to create very complex prototypes. Figure 3 a & b show two such complex prototypes of a cylinder head and gear assembly, respectively, created in Z-Corp Spectrum 510 3DP system. These prototypes clearly show the ability and beauty of this powder based RP technology in mimicking external features of complex geometries.

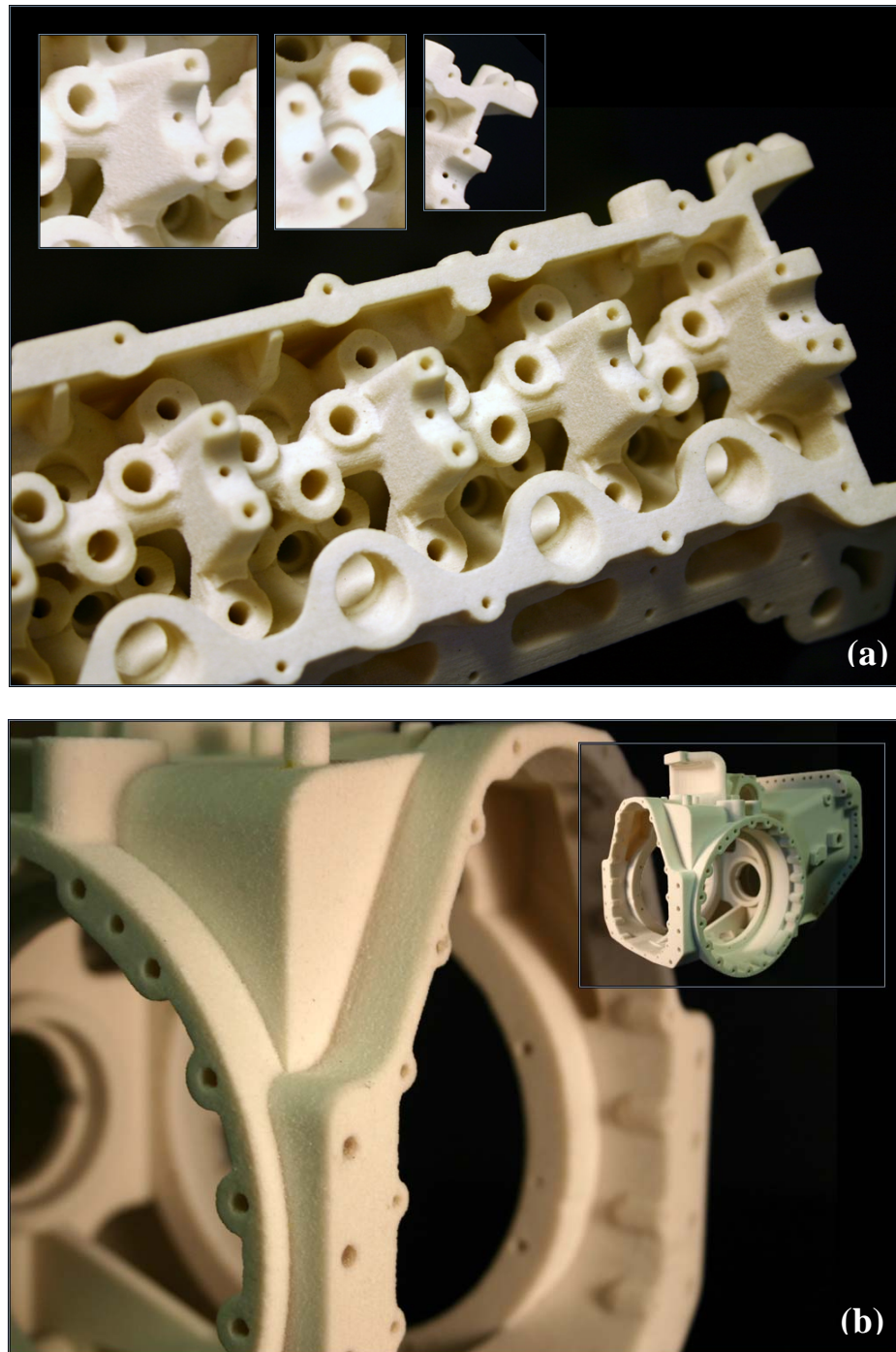


Figure 3: Prototypes having complex geometry created in Z Corporation 3DP machine
(a) a thorough engine block and (b) a detailed gear case. *(Courtesy: Mydea Technologies Corporation, Orlando, FL – printed with permission)*

When infiltrating Z Corporation printed prototypes several methods can be used depending on the infiltrant type. When using a CA three different methods can be used to infiltrate the parts. Parts can be dipped into a vat of CA. This method is fast and effective but requires a large amount of CA. To dip parts a container is filled with CA and the part is lowered slowly into the liquid and maneuvered to fully coat the prototype. The part is then drained and allowed to dry on a nonstick surface. Another method is to drip the CA onto the surface of parts using a small nozzle and squeeze bottle. The drip method is time consuming and does not produce as good of a visual model as the dip method. However large amounts of CA are not required for this method. The third method is to spray the CA using compressed air and a spray gun. The spray method is not used by many users due to the amount of waste produced. The submersing or dripping CA are the preferred methods.

Infiltrating with epoxy varies depending on need. The preferred method for infiltrating with epoxy is to brush the epoxy on the surface. Epoxy is mixed into a container and stirred properly. Then the epoxy is brushed onto the prototype completely coating the part until it will not absorb anymore infiltrant. Parts can be submerged into epoxy similar to with CA. The submersed parts can also be introduced to vacuum or pressure to help the epoxy penetrate the part 100%. Heat can also be introduced to the submersed part to lower the viscosity and increase the absorption of infiltrant into the part.

2.4 Advantages of Z Corporation 3DP

The Spectrum Z510 has many advantages over other 3DP systems. Z Corporation printers are the only RP machines that can print in full 3D color. The Z Corporation 3D printers have the fastest build speed of any machines in the industry. They also have the lowest material cost per cubic inch of any RP machine. The ability to print color increases the amount of different applications the machines can be used. Design engineers can print a part with the finite element analysis directly on the part for design reviews. Parts can be labeled with design changes or notes printed directly on the part. Since the prototypes built on the Spectrum Z510 do not use a support structure (though some geometries do require fixtures that do have associated waste), working assemblies can be printed directly on the machine in one build. Z Corporation also produces a material that can be used to print molds to pour metal into directly. This material allows users to create one off cast metal parts in a much shorter time than traditional methods. These are some of the reasons that Z Corporation printers have become one of the most widely used equipment in the industry.

2.5 Infiltration Options

2.5.1 Cyanoacrylates

Cyanoacrylates (CA) are a one-part liquid adhesive that cures rapidly at room temperature. Cyanoacrylates were first discovered in 1951 when researchers at Tennessee Eastman attempted to measure the refractive index of these materials on an

Abbe refractor and they discovered the prisms of the refractometer had been bonded together [14]. These materials have the ability to cure without the need for an added curing agent unlike epoxies. A variety of materials are used as stabilizers to prevent premature curing of the cyanoacrylate. CA works well as an adhesive and infiltrant due to its rapid rate of initiation with a vast amount of materials. To manufacture alkyl cyanoacrylate monomers, 1, it involves the Knoevenagel reaction of formaldehyde, 2, with an alkyl cyanoacrylate, 3, and a base such as a secondary amine, as the catalyst, shown in figure 4 [14].

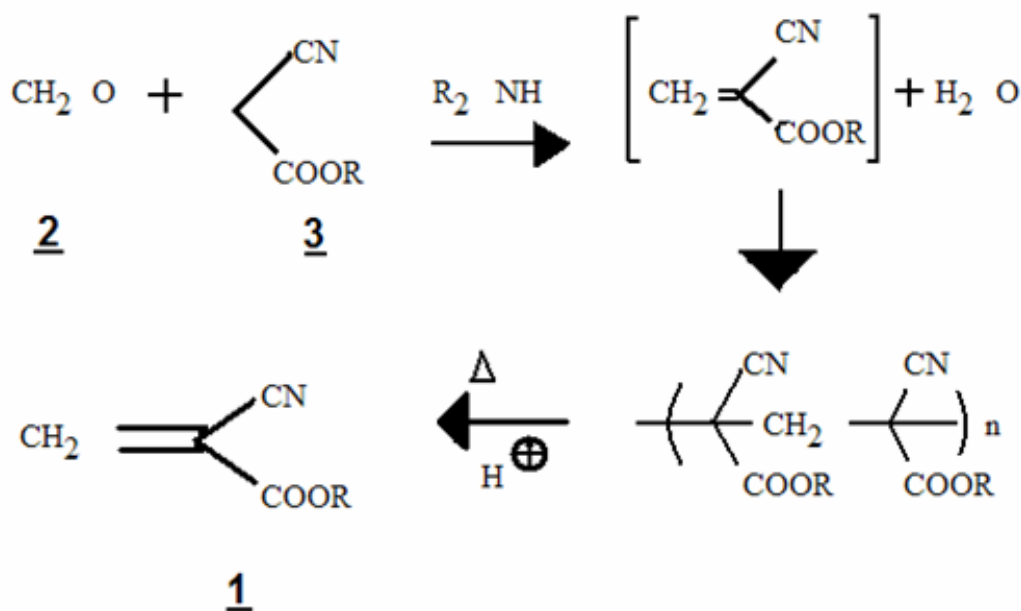


Figure 4: Chemical equation of alkyl cyanoacrylate monomers. [4]

The low viscosity of CA also makes a good infiltrant. There are several different types of CA. The most widely used is ethyl cyanoacrylate due to its fast cure speed and

ease of manufacturing [14]. Cyanoacrylates have several drawbacks such as odor, limited solvent resistance, limited thermal stability [14]. For infiltrating purpose a good monomer is the Methoxethyl because it is a low odor and low bloom CA. A phenomenon that affects Z Corporation parts directly is blooming. Blooming is the formation of a white residue on the surface of the part due to the evaporation of small amounts of the monomer from where it is applied onto the surface [14]. The use of a higher molecular weight monomer can eliminate this problem.

2.5.2 Epoxy

Epoxy resins are considered one of the most versatile polymers with many uses in many different industries. Epoxy resin systems can be used for several applications such as adhesives, potting compounds and molding compounds. Epoxies have several advantages such as excellent adhesion to a variety of materials, relatively low shrink rate, and a cross linked structure that confers excellent resistance to environment [15]. Epoxy is composed of two components, a resin and a curing agent also known as hardner. They are so versatile because they can be formulated to meet a broad range of specific applications [15]. Epoxies are widely used due to their good wetting characteristics and ability to bond with a wide variety of materials. When the two are mixed a chemical reaction occurs turning the epoxy into a solid. Epoxy resins are considered a thermo-set polymer because when cured it is irreversible, rigid, and relatively unaffected by heat [16]. The thermosetting reaction is the joining of many small molecules by chemical reaction to produce an extended network structure. Epoxy

molecules in the pure state can be stored at room temperature for years without reaction [15]. The curing of epoxy creates heat as a result of the chemical reaction. Cured epoxies have good chemical resistance and tensile strength. If the correct amount of resin and hardener are not used the epoxy will not cure properly. Many different types of epoxies are available but the most common is Diglycidyl ether of bisphenol A (DGEBA). The chemical structure of DGEBA is shown in figure 5.

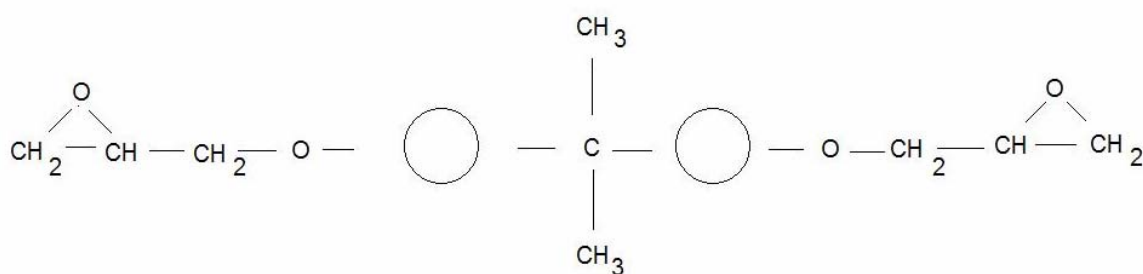


Figure 5: Structure of Diglycidyl ether of bisphenol A (DGEBA) [16].

CHAPTER THREE: METHODOLOGY

3.1 Materials and Equipment Used

Specimens were built in the Spectrum Z 510 using ZP 130 powder along with ZB 58 binder was for this research. The ZB 130 powder is a plaster-based high performance build material [13]. There are numerous variables that can have an effect on the strength of parts. The Z Corporation software has several adjustable build parameters that will affect strength and accuracy, such as shell saturation levels, core saturation levels, bleed compensation, and layer thickness. The shell and core saturation levels refer to the ratio of binder deposited on the outer shell and inner center of the part (figure 6). Turning on bleed compensation can affect the accuracy of parts.

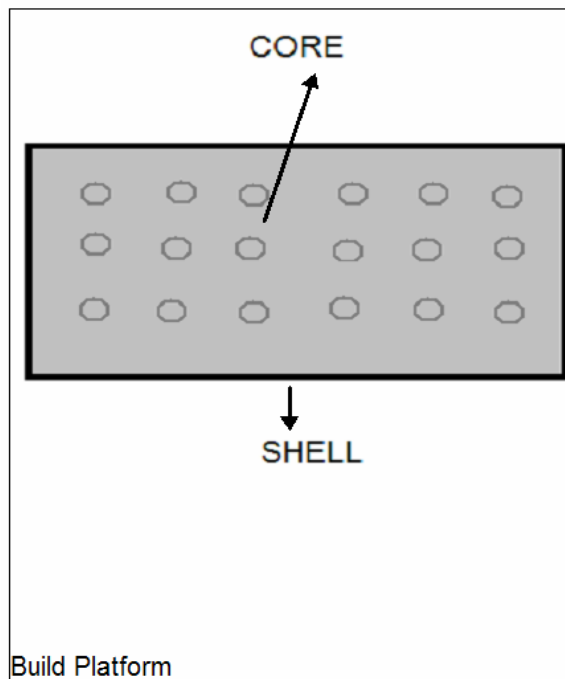


Figure 6: Definition of shell and core structure of prototype.

Some other variables that effect part strength that cannot be controlled with software are build to build variation, print head life, humidity, and other environmental variables. The infiltrant used has the strongest effect on the part strength. The two main types of infiltrants used are cyanoacrylates and epoxies. The use of CA will allow for quicker turnaround due to the fast cure time and it also enhances the appearance of color models. Epoxies are used to give the parts higher strength and durability.

3.2 Phase 1 – Effects of Build Position on Tensile Strength

3.2.1 Specimen Design and Development

The testing specimens were created using Solidworks CAD software package. In addition, a stereolithography (stl) file was exported and used by the printer to create the part. The dimensions of the tensile testing specimen are shown in Figure 7.

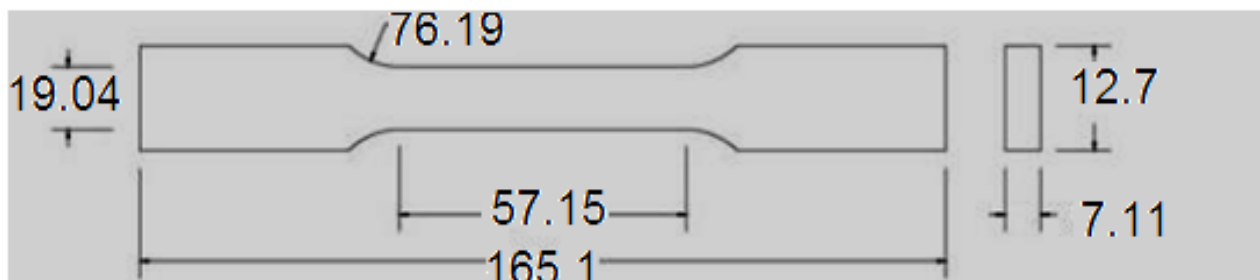


Figure 7: Schematic showing the dimensions of tensile specimen used in this study

The thicker dog bone sample size of 7.11 mm was used to better represent real-world parts. A smaller 3.18 mm thick specimen would allow infiltrants to penetrate the specimen 100% for all infiltrants. Thicker specimens do not allow a part to be completely infiltrated for all infiltrants. When the infiltrant does not penetrate 100%, the core will remain in the green state decreasing the overall strength.

The tensile testing specimens were created with the 3DP process using the default software settings for the Spectrum Z510. Shell and core saturation levels were set to 100%, with the binder/volume ratio 0.276 for the shell and 0.138 for the core. The shell and core saturation levels can be adjusted to vary the binder ratio. The bleed compensation was turned on with default settings (X: 0.0056, Y: 0.0051 and Z: 0.0039) and the layer thickness was set to 0.101 mm for all specimens.

In Phase 1, the specimens were built in the six build zones of the build platform (Figure 8).

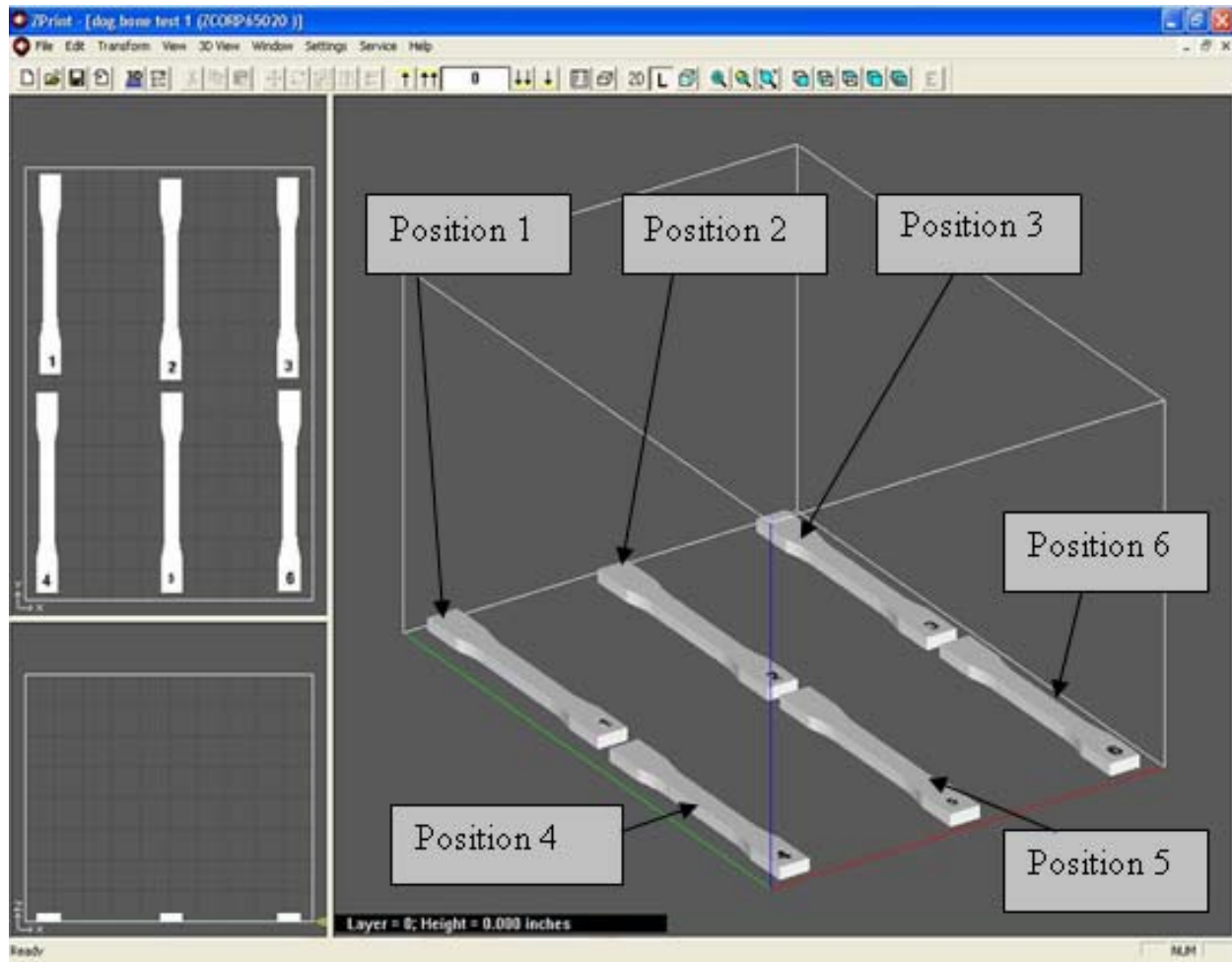


Figure 8: Schematic showing six build zones used to create models for Phase 1 testing

These zones were selected to represent the major building areas of the printer. The specimens were stacked six high in each zone to eliminate the build to build variations. New print heads were installed before each build to ensure the best possible results. Print heads function best for the first third of their life cycle [13]. Once the build was complete, the specimens were left in the Spectrum 510 for an hour. This allows the parts to dry and finish curing before being handled. The parts were then removed from the printer and placed in a convection oven at 82 degrees Celsius for one hour to

remove all of the moisture in the parts. Moisture causes a reaction to start the curing process in cyanoacrylates. If all moisture is not removed from the part it will begin to set before it fully infiltrates into the part. When infiltrating with epoxy, the moisture will limit the amount of epoxy infiltrated and create a weaker part. After the bake cycle, the specimens were completely depowdered. Next the specimens were infiltrated with System Three Clear Coat epoxy. The brush on method was used to apply the epoxy to the dried specimens. Several coats of epoxy were applied until the parts were completely saturated and epoxy would not infiltrate the specimens anymore. They were then allowed to cure at room temperature (25 °C) for 72 hours before testing.

3.3.2 Uniaxial Tensile Testing

Uniaxial tension testing was performed using the screw driven Instron universal tester (Model3369, Instron Co., USA) with a constant crosshead speed of 5 mm/min for all phases. The samples for the position testing were tested following ASTM D638 Standard Test Method for Tensile Properties of Plastics. Following the ASTM standard six samples per build position were tested. The average stress per build location was tested to determine the effect of build location on infiltrated part strength.

3.3 Phase 2 – Effects of Build Orientation on Mechanical Behavior

3.3.1 Specimen Fabrication

Specimens for *Phase 2* were built using the same sample size and following the same procedures as *Phase 1*. The specimens were built in nine different build orientations to determine the effects of build orientation on tensile strength. The samples for the orientation testing were built in nine different orientations along the XYZ coordinate system (Figure 9).

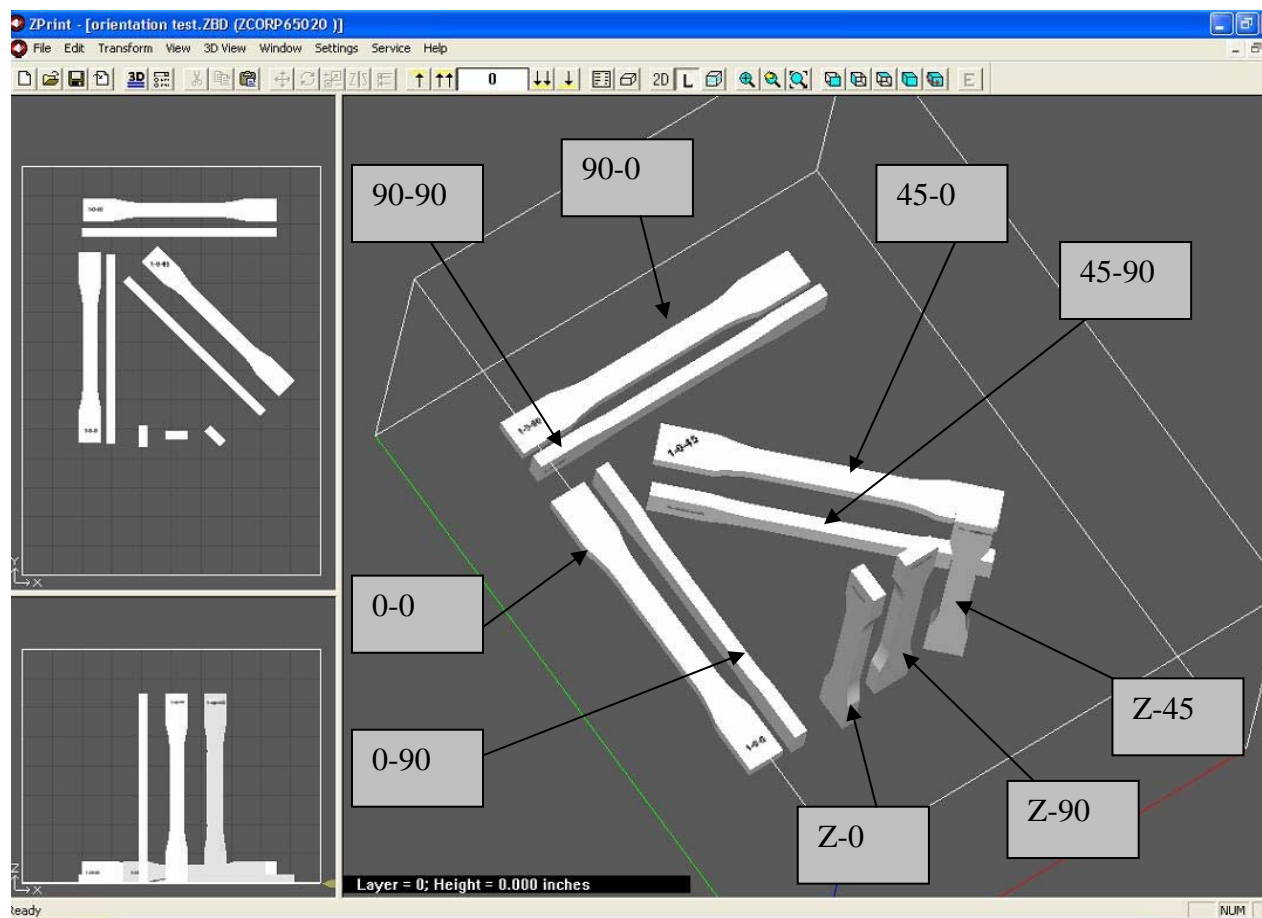


Figure 9: Schematic displaying nine build orientations for phase 2 testing to determine the effects of orientation on tensile strength of prototypes.

The post processing methods for the orientation samples were the same as the position testing samples. The specimens were baked and infiltrated with the System Three Clear Coat Epoxy with the exact same infiltrating process.

3.3.2 Uniaxial Tensile Testing

The uniaxial tension testing was performed using the screw driven Instron 3360 with a constant crosshead speed of 5 mm/min for all phases. The samples for the position testing were tested following ASTM D638 Standard Test Method for Tensile Properties of Plastics. Following the ASTM standard six samples per nine build orientations were tested. The average stress per build orientation was tested to determine the effect of build location on infiltrated part strength.

3.4 Phase 3 – Effects of Infiltrating Material on Mechanical Behavior

3.4.1 Specimen Fabrication

The third phase of the research test is the mechanical properties of seven different infiltrants. Samples were built in three different orientations (Figure 10) using the same sample size and post processing methods as the first two phases. The build orientation for phase 3 was selected based on the results from phase 2. The materials for phase 3 consist of 2 cyanoacrylates and 5 epoxies. Z Corporation distributes a CA (Z-Bond 101) and an epoxy (Z Max) to be used with the 3DP system. These materials were used as a baseline for testing. Of the 5 epoxies tested two were high temperature epoxies (HTR 212 and EEL 335). The seven materials and cost per ounce are in Table 1.

Table 1

Cost comparison of materials used during infiltration of Z Corporation samples

Infiltrant	Type of Infiltrant	Cost per Ounce
Z Bond 101	Cyanoacrylate	\$12.75
CA Plus N5	Cyanoacrylate	\$9.06
Z Max	Epoxy	\$1.61
System Three Clear Coat	Epoxy	\$0.85
Ad-Tech Epoxy CER-112	Epoxy	\$1.30
Resin Services HTR-212	High-temp Epoxy	\$0.58
Ad-Tech Epoxy EEL-335	High-temp Epoxy	\$0.62

The process for infiltrating with the high temperature epoxies is the same until the curing process. Once the samples are infiltrated they are left to cure at room temperature for 24 hours then placed in a convection oven and heated. The samples are baked from 82 degrees C up to 176 degrees C increasing the temperature 50 degrees every hour.

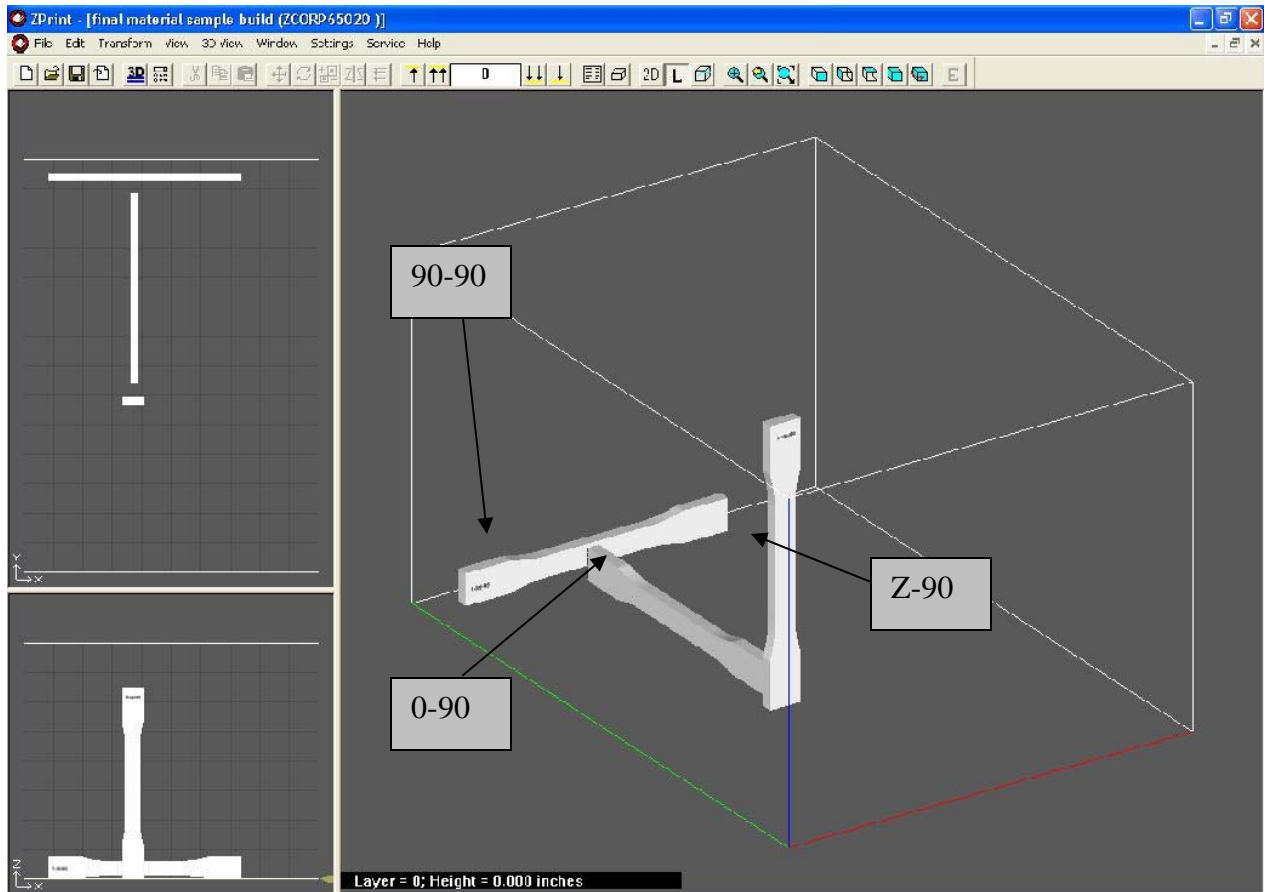


Figure 10: Diagram to display the three build orientations for Phase 3 Material infiltration testing

3.4.2 Density and Porosity Measurement

The geometric bulk density (ρ_g) in each build orientation and material was determined from the specimens used in phase 3. To determine the geometric bulk density a section of the specimen was cut to a uniform size to determine the volume. The specimens were then weighed to determine its mass and the geometric bulk density was calculated using equation 1.

$$\text{Geometric Bulk Density } (\rho_g) = \text{Mass/Volume} \quad (1)$$

The porosity and volumetric bulk density of the seven infiltrating materials were determined using the immersion technique. The apparent density is the ratio of the mass in air to a given volume at a stated temperature. Porosity of a material is the measure of the percentage of water permeable voids in a compacted sample. Specimens were soaked in pure water for 2 hours. The specimens were removed from the water, drained and dried off. Then the samples were weighed for the saturated mass when the surface dry condition was reached. The samples are then measured again to find the total weight in water at 25.5 °C the immersed mass (m_i). The samples are baked to complete the drying process and measured for the dry mass (m_d). Equations (2) and (3) were used to determine the volumetric bulk density (ρ_v), and the apparent density (ρ_a). The apparent porosity (ζ_a) of the specimens were evaluated using equation (3), where as ρ_L is the density of the liquid.

$$\rho_v = \left[\frac{m_d}{(m_s - m_i)} \right] \cdot \rho_L \quad (2)$$

$$\rho_a = \left[\frac{m_d}{(m_d - m_i)} \right] \rho_L \quad (3)$$

$$\zeta_a = 100 \left[\frac{(m_s - m_d)}{(m_s - m_i)} \right] \quad (4)$$

3.4.3 Specimen Infiltrant Absorption

The samples for phase 3 were weighed in air after drying and before infiltration. They were also weighed after the final curing of infiltrated specimens. The percentage of infiltrant absorbed by the specimens in phase 3 was determined to relate to the tensile strength of the specimens. Equation 4 was used to determine the percentage of infiltrant absorbed based on weight change [17].

$$\text{infiltrant absorbtion percent} = \frac{\text{weight after infiltrant(g)} - \text{initial weight(g)}}{\text{initial weight(g)}} \times 100 \quad (5)$$

3.4.4 Uniaxial Tensile Testing

Testing was performed in three phases. In each phase, tensile testing was performed following ASTM D638 testing six samples per test. Phase 1 - Position Testing was to determine how the build position affected tensile strength. Phase 2 - Orientation Testing was to determine if build orientation effects tensile strength. Finally, Phase 3 - Infiltration Materials were tested to determine strength of several different infiltrants.

3.4.5 3-Point Bend Testing

Flexural testing was performed using the seven materials and build orientations of Phase 3 for infiltration. Specimens were created using the same methods as tensile testing. Testing was performed using the Instron 3360 and the flexural testing setup.

The flexural testing specimens were created with a 7.11 mm thickness. The testing was performed according to ASTM D790 using the three point method and six samples per test. The cross head speed was set to 0.119 mm/mm/min.

3.5 Statistical Analysis

The t test is a statistical method to determine the significance of results between groups of data. The t test tells if the variation between two groups is significant. Multiple t tests can not be used because as the number of groups grows, the number of pair comparisons grows. Using seven groups there would be 21 pairs.

The analysis of variance (ANOVA) is performed to determine the significance of testing of three or more groups. ANOVA puts all of the data into one number and gives one P value for the null hypothesis. The ANOVA procedure attempts to analyze the variation in a set of responses and assign portions of this variation to each of a set of independent variables [18]. The objective of analysis of variance is to locate the important independent variables and determine how they affect the response [18, 19]. In this research there is only one factor, stress, therefore a one way ANOVA is used to determine significance.

The results for ANOVA are displayed in a table format. The first column gives the source associated with each sum of squares of deviation; the second column gives the corresponding sums of squares (SS); the third and forth columns give the degrees of freedom (df) and mean squares (MS), respectively [18]. A calculated value of F is usually shown in the fifth column. The F test is used in testing the equality of treatment

means. The last two columns display the P value and the F critical value respectively. The F critical value is a tabular value of the F distribution based on the chosen alpha level and the degrees of freedom.

CHAPTER FOUR: RESULTS

4.1 *Phase 1* Effects of Build Location on Tensile Strength

Phase 1: Position Testing was performed to determine if build placement had an effect on the tensile strength of parts. When the powder is spread for the new layer it is spread from left to right, therefore it is believed that the density of powder in zones 1 and 4 will be greater and will produce stronger parts. The average stress of the samples for all build zones was within 1.1 MPa. The samples built in zone 2 had the highest average stress but also had the largest error. A graph of the average tensile stress for the six different build zones is shown in Figure 11.

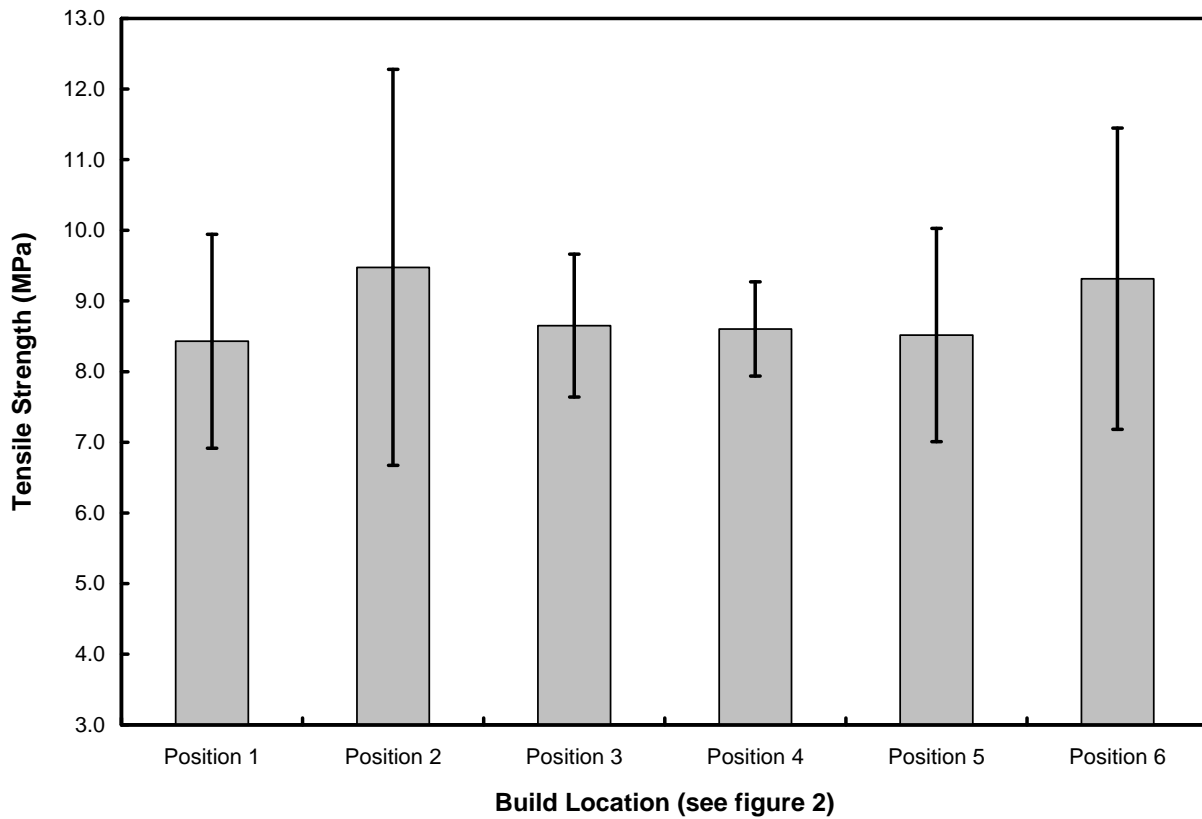


Figure 11: Graph of the average tensile strength of Z Corporations samples infiltrated with System Three Clear Coat Epoxy built in the six different zones

Statistical analysis was performed to determine the significance of the results for the position testing. The large P value shows that these results did not have a great significance. The ANOVA results are shown in table 2 below.

Table 2 Anova analysis for position testing

Anova: Single Factor

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Build Position 1	6	50.59	8.43	2.30
Build Position 2	6	56.86	9.48	7.86
Build Position 3	6	51.91	8.65	1.02
Build Position 4	6	51.63	8.60	0.45
Build Position 5	6	51.11	8.52	2.28
Build Position 6	6	55.89	9.31	4.55

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	5.95	5	1.19	0.39	0.85	2.53
Within Groups	92.25	30	3.07			
Total	98.19	35				

4.2 Phase 2 Effects of Build Orientation on Tensile Strength

Phase 2: Orientation Testing was performed to determine if the build orientation of parts has a large effect on the strength of the final part. The parts built in 0-90 and 90-90 orientations had a higher average stress (17.9MPa and 16.78MPa respectively) than the other orientations. Specimens built in the vertical Z direction had the lowest tensile strength. The average tensile stress for each build orientation is shown in Figure 12.

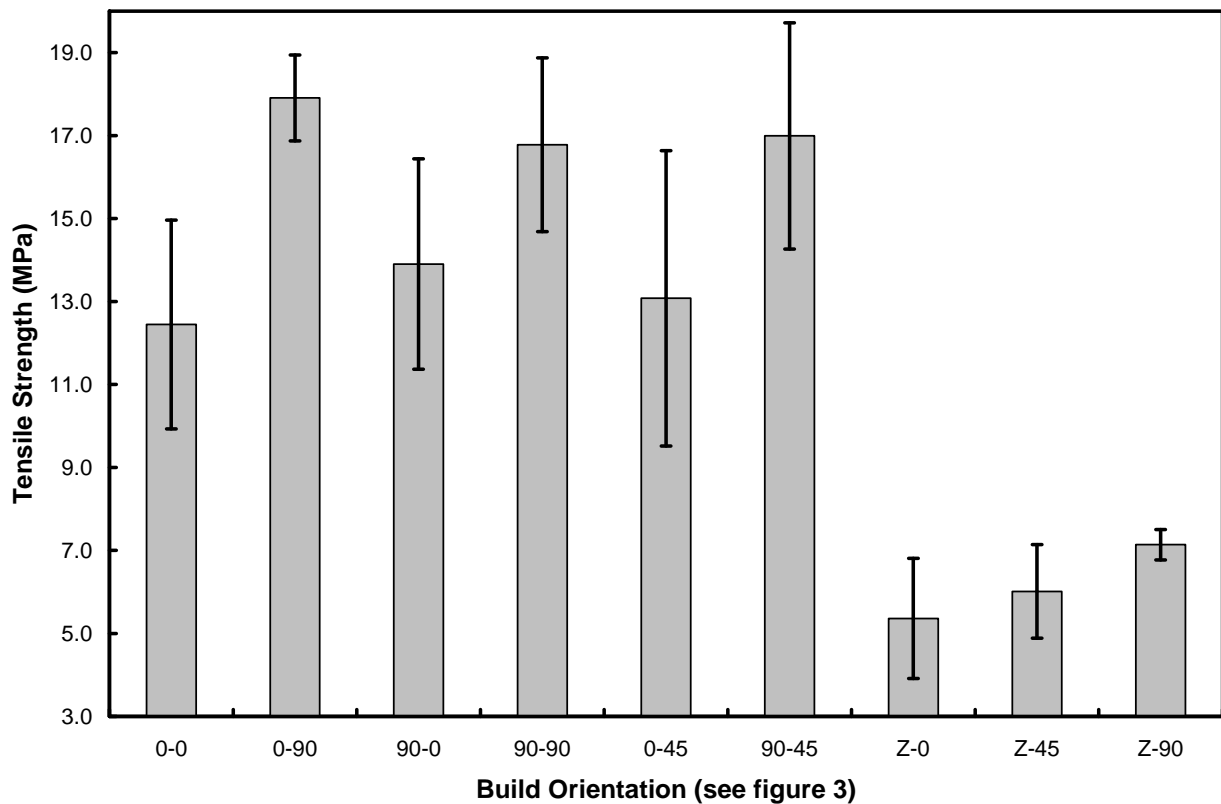


Figure 12: Graph of the average tensile strength of Z Corporations samples built in nine different orientations infiltrated with System Three Clear Coat Epoxy

The statistical significance of the orientation testing was determined using the Analysis of Variance testing. It was determined that the results of the orientation testing were highly significant with a P value of 1.11×10^{-15} . Table 3 displays the results of the ANOVA testing.

Table 3 Anova for orientation testing

Anova: Single Factor

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Build Orientation 0-0	6	74.68	12.45	6.32
Build Orientation 0-90	6	107.43	17.90	1.08
Build Orientation 90-0	6	83.43	13.90	6.41
Build Orientation 90-90	6	100.70	16.78	4.37
Build Orientation 0-45	6	78.43	13.07	12.63
Build Orientation 90-45	6	101.91	16.98	7.45
Build Orientation z-90	6	42.17	7.03	0.06
Build Orientation z-0	6	33.15	5.52	2.28
Build Orientation z-45	6	37.77	6.30	0.86

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	1118.02	8	139.75	30.34	1.11x10 ⁻¹⁵	2.15
Within Groups	207.25	45	4.61			
Total	1325.28	53				

4.3 Phase 3 Effects of Infiltrating Material on Mechanical Behavior

Phase 3: Infiltrant Testing was to determine what affects the different infiltrants used with Z Corporation on the parts strength. The samples were built in three orientations; 0-90, 90-90, and Z-90. The x-90 orientation had the highest strength and smallest error from phase 2. During phase 3 two different CAs were used, both with a viscosity of

2cps. These materials both had the same penetration depth within ± 0.254 mm. The samples infiltrated with the CA Plus had a higher strength. Specimens infiltrated with CA Plus had an average of 5MPa while Z Bond 101 had an average of 3.5MPa. The CA materials displayed the smallest error among all infiltrating samples.

The average tensile strength for the seven infiltrating materials in all three build orientations is shown in Figure 13. The epoxy branded by Z Corporation (Z Max) produced the highest average stress of 17.87 MPa in the 0-90 build orientation. All three build orientations were fairly consistent within 2.5 Mpa of each other. The materials with the lowest tensile strength were the high temperature epoxies and they also had the shallowest penetration depth of infiltrants. The System Three Clear Coat epoxy and CER 112 epoxy were comparable in tensile strength.

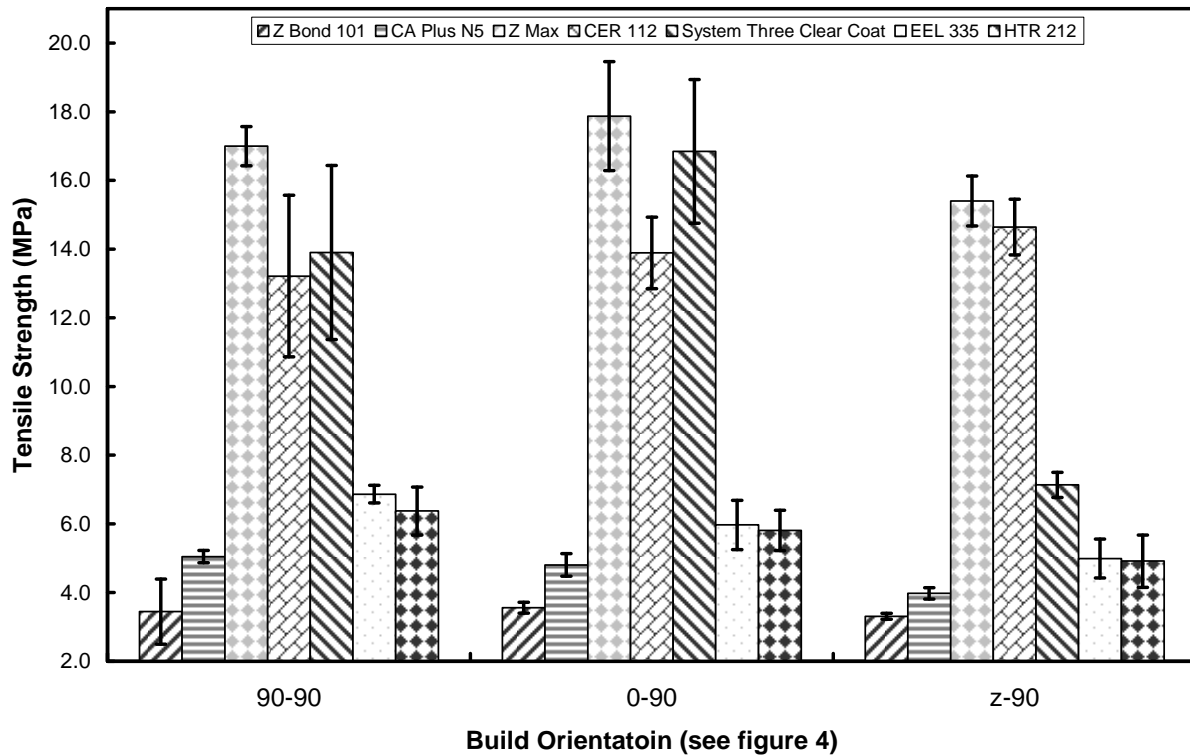


Figure 13: A comparative plot showing the average tensile strength of samples built in three orientations and infiltrated with seven different materials

The testing performed for the seven different infiltrating materials was determined to be highly significant using ANOVA testing. The P value of 1.47×10^{-66} shows that these results have a great significance. The ANOVA results are shown in table 4 below.

Table 4 Anova for infiltration material

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Z Max Build Orientation 90-90	6	101.98	17.00	0.33
Z Max Build Orientation 90-0	6	107.26	17.88	0.53
Z Max Build Orientation z-90	6	92.41	15.40	2.52
System Three 90-90	6	100.68	16.78	4.38
System Three 90-0	6	83.42	13.90	6.41
System Three z-90	6	42.17	7.03	0.06
CER 112 90-90	6	79.30	13.22	5.55
CER 112 90-0	6	83.35	13.89	0.65
CER 112 z-90	6	87.89	14.65	1.09
EEL 335 90-90	6	41.20	6.87	0.07
EEL 335 90-0	6	35.83	5.97	0.32
EEL 335 z-90	6	29.94	4.99	0.51
HTR 212 90-90	6	38.26	6.38	0.49
HTR 212 90-0	6	34.86	5.81	0.58
HTR 212 z-90	6	29.50	4.92	0.35
Z Bond 90-90	6	20.68	3.45	0.89
Z Bond 90-0	6	21.38	3.56	0.01
Z Bond z-90	6	19.86	3.31	0.03
CA Plus 90-90	6	30.29	5.05	0.03
CA Plus 90-0	6	28.80	4.80	0.03
CA Plus z-90	6	23.86	3.98	0.11

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3363.58	20	168.18	141.69	1.47x10^-66	1.67
Within Groups	124.63	105	1.19			
Total	3488.21	125				

The average flexural strength of Z Corporations samples infiltrated with seven different materials and built in the three different orientations from phase 3 is shown in Figure 14. The Z Corporation epoxy, “Z Max,” displayed the highest flexural strength of

36.06 MPa in the 90-90 build orientation. The specimens infiltrated with cyanoacrylates experienced the lowest average flexural strength. The high temperature epoxies had higher flexural strength than expected based on tensile testing.

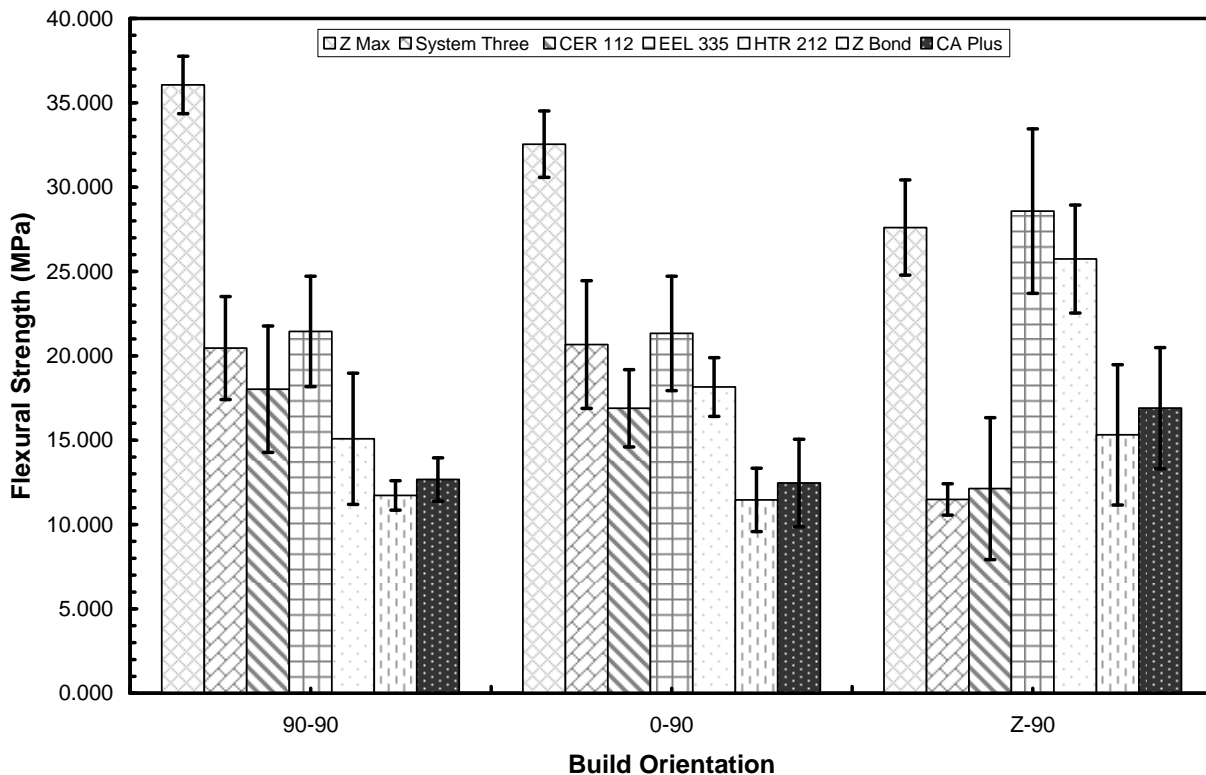


Figure 14: Graph of the average flexural strength of Z Corporations samples infiltrated with seven different materials and built in the three different orientations from phase 3

The statistical significance of the 3pt bend testing was determined using the Analysis of Variance testing. It was determined that the results of the orientation testing were highly significant with a P value of 1.07×10^{-36} . Table 5 displays the results of the ANOVA testing.

Table 5: Results of ANOVA analysis of three-point bend test results

Anova: Single Factor

SUMMARY

<i>Groups</i>	<i>Count</i>	<i>Sum</i>	<i>Average</i>	<i>Variance</i>
Z Max Build Orientation 90-90	6	216.35	36.06	2.89
Z Max Build Orientation 90-0	6	195.28	32.55	3.86
Z Max Build Orientation z-90	6	165.64	27.61	7.95
System Three 90-90	6	122.75	20.46	9.30
System Three 90-0	6	124.03	20.67	14.31
System Three z-90	6	68.93	11.49	0.86
CER 112 90-90	6	108.15	18.02	14.06
CER 112 90-0	6	101.35	16.89	5.23
CER 112 z-90	6	72.77	12.13	17.68
EEL 335 90-90	6	128.68	21.45	10.73
EEL 335 90-0	6	127.99	21.33	11.49
EEL 335 z-90	6	171.47	28.58	23.75
HTR 212 90-90	6	90.50	15.08	15.09
HTR 212 90-0	6	108.92	18.15	3.03
HTR 212 z-90	6	154.45	25.74	10.22
Z Bond 90-90	6	71.28	11.88	0.51
Z Bond 90-0	6	68.76	11.46	3.52
Z Bond z-90	6	91.90	15.32	17.28
CA Plus 90-90	6	76.04	12.67	1.65
CA Plus 90-0	6	74.78	12.46	6.75
CA Plus z-90	6	101.38	16.90	12.90

ANOVA

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Between Groups	6194.94	20	309.74	33.69	1.07x10 ⁻³⁶	1.67
Within Groups	965.30	105	9.19			
Total	7160.24	125				

The geometric bulk density was calculated for each build orientation and infiltration material from phase 3. Figure 15 represents the geometric bulk density of the samples from phase 3. Specimens infiltrated with Z Max had the highest bulk density. When all infiltrating materials were compared the geometric bulk density was consistent

among the specimens. The geometric bulk density results show that the density of parts has an affect on part strength.

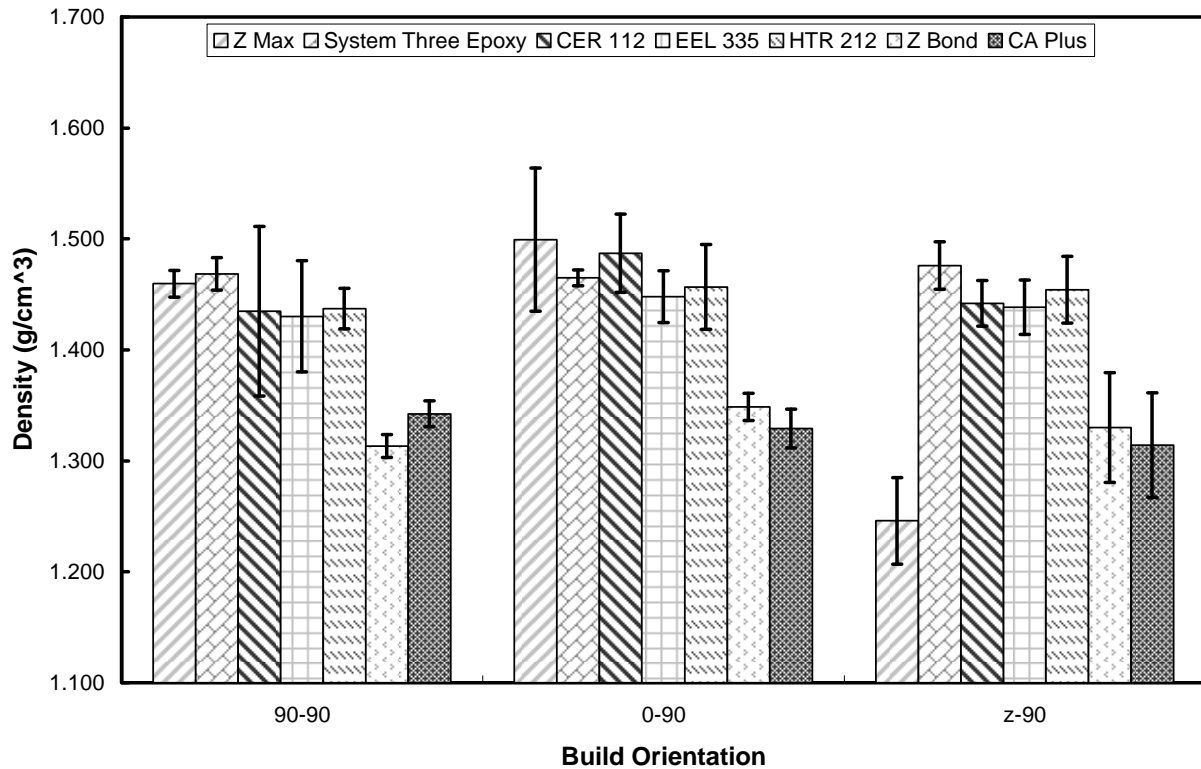


Figure 15: Geometric bulk density of 3DP specimens infiltrated with the seven infiltrating materials in phase 3

The porosity and apparent density were determined using the same samples from the bulk density. Figure 16 is a comparison of the porosity for the seven infiltration materials.

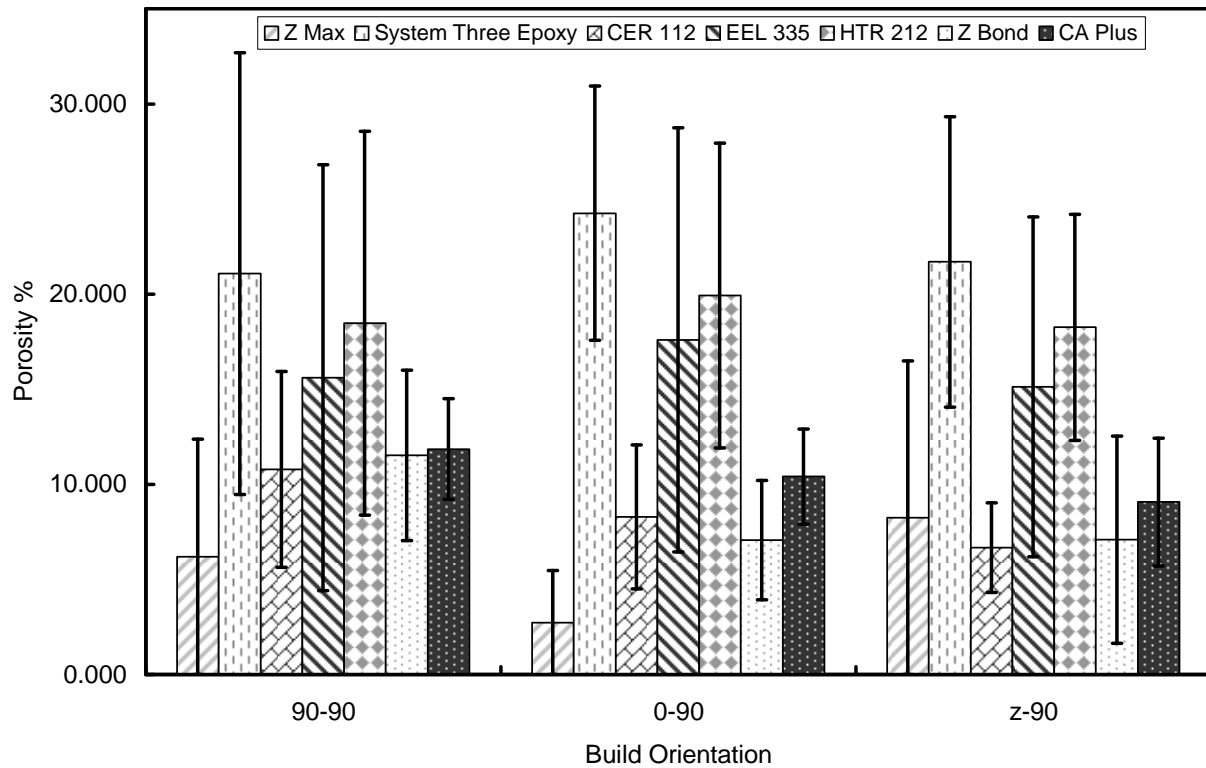


Figure 16: Porosity of 3DP specimens infiltrated with the seven infiltrating materials in phase 3

The infiltrated specimens with the lower porosity experienced higher tensile strength. The Z Max infiltrant had the lowest porosity average of all build directions at 8.59% and it had the highest strength. The high temperature epoxies have a high porosity due to the infiltrant not penetrating completely into the part. The two CA materials had a relatively low porosity and tensile strength. The apparent density (Figure 17) of the specimens was relatively higher than the geometric bulk density.

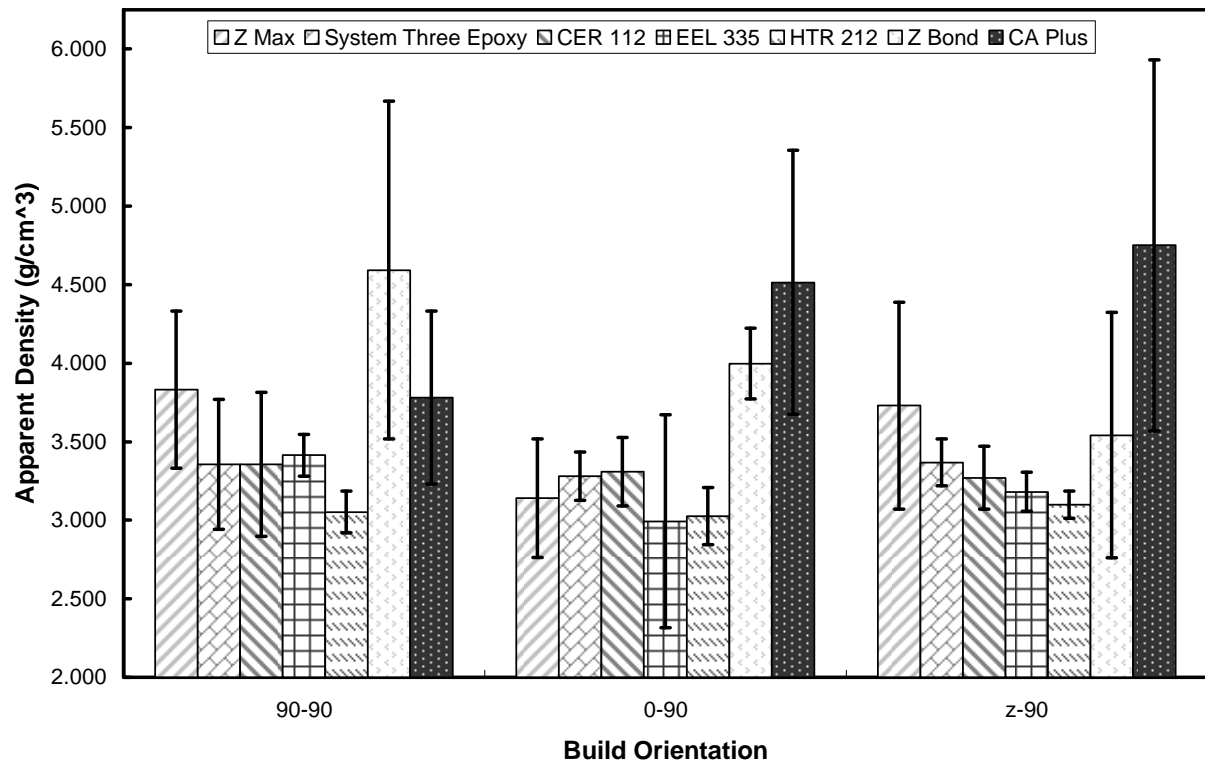


Figure 17: Apparent density of 3DP specimens infiltrated with the seven infiltrating materials in phase 3

The cyanoacrylates had a higher apparent density than other materials. The epoxies displayed the same ranking order as in bulk density. Figure 18 is a plot of porosity against the tensile strength of the specimens infiltrated with seven different materials.

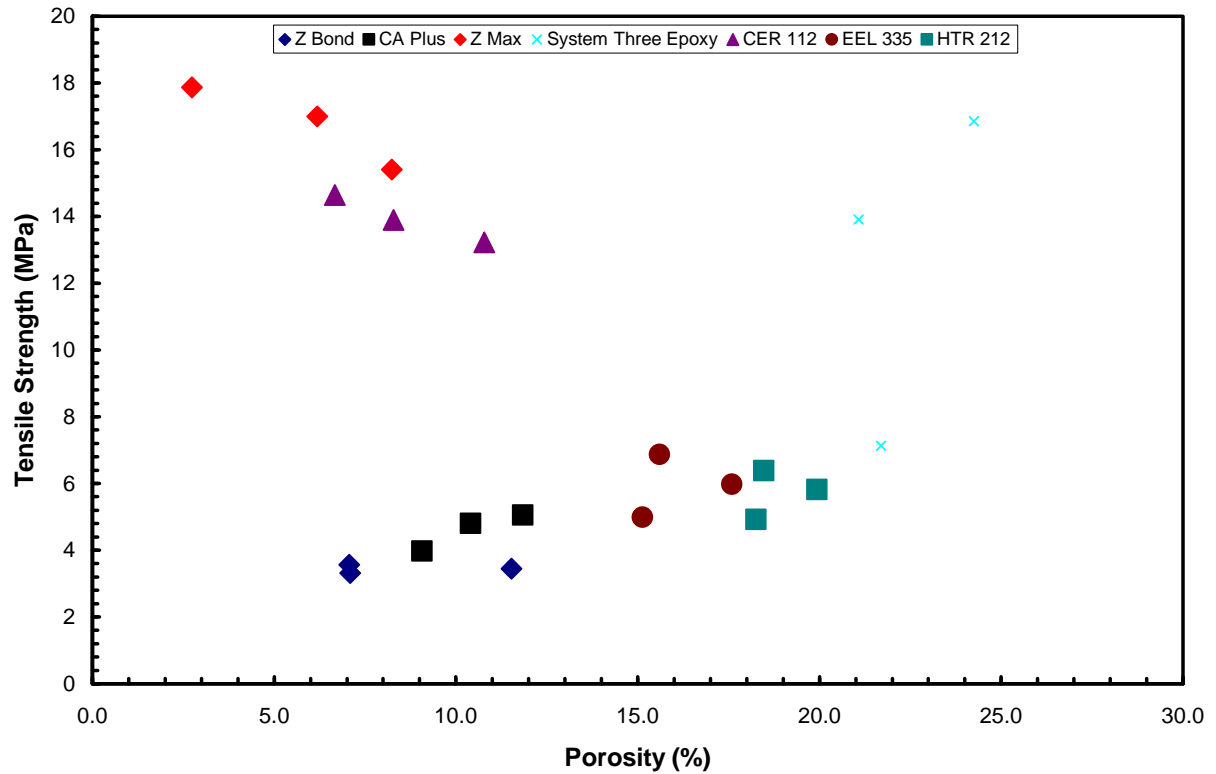


Figure 18: Plot of tensile strength vs. porosity of samples infiltrated with seven infiltrants

The specimens for phase 3 were weighed before and after infiltrating to determine the amount of material absorbed. The amount of infiltrant absorbed is consistent with the tensile strength/porosity relationship. The three regular temperature epoxies absorbed the most infiltrant and had the highest tensile strength see figure 19.

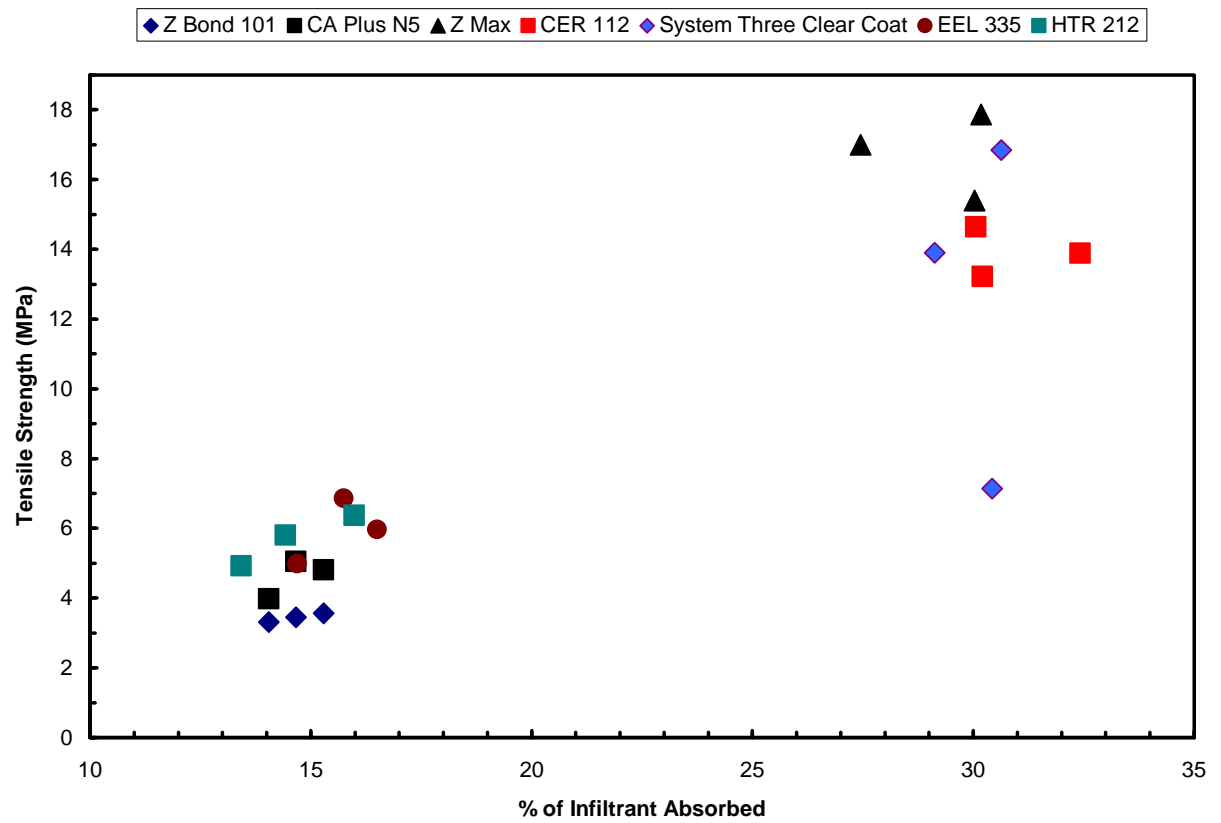


Figure 19: A graph of the amount of infiltrant absorbed vs. tensile strength

CHAPTER FIVE: DISCUSSION

The results of the build position testing were not consistent with suggestions of build placement by Z Corporation. It is suggested that you build parts in zone 1 (default build location) for the highest strength and speed. An optimization study was performed on placement that suggest placing parts to the far right in zones 3 or 6 for best results [12]. The zone that showed the highest strength also had the largest error among specimens. The large error could be due to several build and post processing variables such as moisture in parts before infiltration or the infiltrated density variation between samples. Due to the tensile strength of all build position being similar the results from the position testing show that the build placement of parts does not have a large impact on tensile strength. It can be concluded that build location does not have a large impact because most of the part strength is determined by the infiltration material.

The build orientation of parts has a larger effect on the tensile strength of the final part than the build location. Due to the layering build process of RP parts, the parts printed in the Z direction have a lower tensile strength when compared to the other build orientations. The bond between layers is not as strong as each layer itself. Therefore when tension is applied along the direction of the 2D profile the parts were stronger then when applied in the direction of layers. The z direction specimens also had a lower tensile strength because they absorbed the smallest amount of infiltrant for most samples. The parts built in the 0-90 and 90-90 orientations had higher average strength than the other build orientations. This is partially due to the infiltrant penetrating deeper into side walls of a part than the up facing surfaces of a sample [13]. The parts build in

the x-90 orientation had a high strength due to the binder depositing method. As the part is printing the binder is deposited from back to front then right to left of the build area. When specimens were placed in the 0-x orientation the cross section of specimen is completed in one pass from back to front. The samples placed in the x-90 orientation take several passes back to front to complete the cross section left to right. The staggering of the passes for each of the cross sections creates a stronger part due to the overlap of sections. Due to significant lack of literature on mechanical properties of parts created using 3DP system, we could not compare our findings. Research on 3DP system has so far been restricted to its accuracy in printing and surface finish and, studies on effect of resin infiltration technique. Dimitrov *et al.* investigated the achievable accuracy of three dimensional printing [6]. The same group also published another informative review article on 3DP discussing its pros and future prospects [8]. Suwanpateeb demonstrated the governed factors which need to be considered for using 3DP models in moisture resistance application [20]. Steele *et al.* studied the effect of resin infiltration techniques on parts produced in 3DP system [21]

The viscosity of infiltrating materials has a large effect on the amount of infiltrant absorbed by the specimen. This also has a large effect on the overall part strength. The cyanoacrylates had the lowest viscosity of all materials used for infiltration. CAs cure rapidly and do not penetrate the samples 100% like the epoxies can. The infiltrant will only penetrate the surface approximately 0.254 mm resulting in a weaker part than if infiltrated with epoxy, because there is only a surface coat to harden the specimen and the core is still in the green state. The samples infiltrated with CA have a shorter cure time and produce brighter color models. The samples infiltrated with the

cyanoacrylates displayed lower strength due to the shallow penetration depth. The amount of infiltrant absorbed into the specimen was much lower for cyanoacrylate specimens than epoxy.

One of the main factors of selecting an epoxy infiltrant is the viscosity. If the viscosity is too high it will not penetrate completely into the part which lowers the part strength. The lower the viscosity is the higher the infiltrant absorption possibilities. The high temperature epoxy materials have a viscosity of 800-1000 cps. The high viscosity limited the penetration depth to around 0.765 mm using the same infiltrating method. This resulted in a relatively low tensile strength compared to the other epoxies. Z Max epoxy has the lowest viscosity and produced the highest tensile strength and flexural strength. The epoxies tested, with the exception of the high temperature epoxy, have a viscosity lower than 600 cps. As the viscosity of the epoxy increased the tensile strength of the parts decreased. However, the high temperature epoxies had the second and third highest flexural strength of the epoxies.

The density of the specimens has a large impact on its tensile and flexural strength. When infiltrating with an epoxy the material will penetrate deeper into the part forming a bond within the internal structure. It is for this reason that epoxies have a higher density than CA infiltrants. Z Max was the epoxy with the lowest viscosity, which resulted in the highest density and lowest porosity. A high porosity means that voids are present in the parts that were not filled with the infiltrants. The Spectrum Z510 produces parts in the green state with a high porosity around 50 percent to allow for maximum infiltrant absorption [22]. If the voids are not filled to full potential a weaker part is produced.

CHAPTER SIX: CONCLUSIONS

This research effort investigated the effects of build position, build orientation, and infiltration material on part strength of prototypes created in 3DP. This work revealed that the build position does not have significant impact on tensile strength. In addition, It was shown that build orientation does have an effect on tensile strength. However it was also shown that infiltration material has the largest effect on the strength of prototypes. The CA is a faster infiltration method and produces brighter color models but has a lower tensile strength compared to epoxies. Cyanoacrylates should be used if a good color concept model is needed and the CA Plus infiltrant is the recommended CA infiltrant. Some major factors in part strength are the amount of infiltrant absorbed, the density and porosity of the sample after infiltrated with epoxy. A weaker part is produced if the infiltrant does not penetrate completely into the part and create a bond in the core of the prototype. When the strongest possible part built on a Spectrum Z510 is needed, the ZMax epoxy should be used. If both cost and strength are important factors, then System Three Clear Coat epoxy is a good choice. The Z Corporation 3DP process can make a larger impact in direct digital manufacturing, rapid tooling, and fit and functional models with the increase of infiltrating materials.

CHAPTER SEVEN: FUTURE WORK

Future research based on my MS research thesis can be planned to address several important issues including the research to study several other infiltrating materials which could not be completed in this work. Urethanes were not tested in this study but could work well as an infiltration material. Post processing methods could also be varied to produce different results. Varying the post bake drying time may have significant effects on the part strength. The infiltration method could possibly affect the overall strength of the final part. This study used the drip/brush on method for infiltration. Other methods include dipping or soaking the parts. The accuracy should also be tested based on infiltration material. Specimens can also be infiltrated under pressure or vacuum while varying the heat during infiltration. This will change the viscosity of the infiltration materials. The higher temperature along with vacuum, or pressure might allow the infiltrants to penetrate the specimen deeper, possibility lowering the porosity increasing strength. Using new infiltrants it may be possible to use 3DP for investment casting. Testing will need to be performed adjusting parameters and materials.

The Spectrum Z510 has several build variables that can be adjusted to affect the final parts. The shell and core saturation levels can be adjusted which might affect part strength. If the core levels are lowered the part might absorb more infiltrants resulting in a stronger part. As new materials are discovered the list of infiltrants will continue to grow and should be tested.

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